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IN REDUCED GRAVITY FROM  
HORIZONTAL AND VERTICAL WIRES

*by Robert Siegel and Edward G. Keshock*

*Lewis Research Center*

*Cleveland, Ohio*

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SUMMARY

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Nucleate boiling was studied experimentally from electrically heated horizontal and vertical wires (0.0197-in. diam.) in water, ethyl alcohol, and 60-percent-by-weight aqueous sucrose solution in gravity fields of 0.014 and 1.0 times Earth gravity. The fluids were at their saturation temperatures at atmospheric pressure. The gravity reduction to 0.014 times Earth gravity caused a shift of only a few degrees in the curve of heat flux as a function of the difference between surface and saturation temperatures.

Film boiling of ethyl alcohol was observed at Earth gravity and at several reduced gravity fields down to 0.014 times Earth gravity. For both the horizontal and the vertical orientations, the gravity field and the circumferential surface tension at the interface of the vapor film surrounding the thin wire proved to be very important for the determination of the vapor removal pattern. As gravity was reduced, the vapor film behavior for the vertical orientation approached that for the horizontal position. A motion picture film is available that illustrates the boiling behavior in reduced gravity.

Author ↑

INTRODUCTION

Until several years ago, experiments on boiling heat transfer had all been conducted at Earth gravity conditions. Although a gravity parameter was present in some of the theoretical analyses and experimental correlations, no experimental evidence had been obtained to verify whether the indicated gravity dependence was correct. An interest in boiling performance at gravity fields other than Earth gravity arose with regard to the design of heat-transfer devices for space-vehicle applications. Space vehicles may undergo periods of acceleration and coasting, and the body forces may, accordingly, be greater or less than the body force experienced under stationary conditions on Earth. As a result, various studies have been initiated to examine both reduced and increased gravity effects. The present report is concerned with nucleate pool boiling and film boiling from thin wires in a reduced-gravity environment for saturated liquids at atmospheric pressure.

Reference 1 was devoted mainly to the effect of gravity reductions on the critical (burnout) heat flux. An electrically heated horizontal wire was used as a test section in a boiler situated on a counterweighted drop tower. The test results showed that the burnout heat flux decreased with gravity approximately as  $g^{1/4}$ , as indicated by theory. In the nucleate range, the data indicated that the curve of heat transfer as a function of the difference between surface and saturation temperatures was unaffected by gravity reductions. The instrumentation in these tests, however, could not detect surface temperature changes less than several degrees.

In reference 2, nucleate boiling of liquid hydrogen from a horizontal surface in zero gravity was studied in both drop tower and airplane tests. Test times up to 15 seconds were obtained in the airplane tests. The zero-gravity nucleate-boiling heat transfer was essentially the same as the  $1-g_n$  results. Photographic observations showed that after the bubbles formed at the heated surface, coalesced, and departed, the surface tension was sufficiently large, in all cases, to rewet the surface behind the bubbles.

In reference 3, some results are reported for nucleate boiling of water at and near zero gravity that were obtained by using an airplane that provided test times up to 17 seconds. When the gravity field was  $0.03 g_n$ , the boiling heat transfer was not changed from that in  $1 g_n$ . (All symbols are defined in appendix A.) For  $0.01 g_n$ , however, the lack of convection currents caused the fluid to become stratified with a higher temperature layer near the heated surface. This stratification caused a pressure rise in the closed boiler, and the bulk of the fluid away from the surface thereby became subcooled. The vapor was observed to condense slowly in the subcooled liquid, probably because of the lack of free-convection circulation of the liquid around the bubbles. Because of the rising pressure, a steady state was not reached for very low gravities during the 17-second test duration.

Boiling heat-transfer rates for nucleate, transition, and film boiling of liquid nitrogen in reduced and near zero gravity were obtained using a counterweighted drop tower (ref. 4). Nucleate boiling again proved to be insensitive to gravity reductions for the test times available. It was concluded in reference 4 that even in saturated liquids, the controlling factor in nucleate boiling is probably the dynamic (or inertial) force arising from bubble growth rather than the buoyancy force.

Some tests conducted concurrently with the present work are described in reference 5. A drop tower providing 1.85 seconds at  $0.01$  times Earth gravity was used to investigate nucleate boiling and the critical heat flux in saturated water. Electrically heated platinum ribbons and wires in a horizontal orientation were used as test sections. The tests revealed that, for nucleate boiling, the pool-boiling process is enhanced by a reduction in gravity but the effect is small. This relative insensitivity to gravity was explained in terms of the prominence of the liquid dynamic forces resulting from bubble growth. Some very interesting photographs of burnout in  $0.01 g_n$  are also included.

Nucleate boiling in a saturated liquid has also been shown to be fairly insensitive to gravity by means of tests at increased gravity fields. Results



in references 6 and 7 for boiling from a horizontal cylindrical surface in distilled water showed shifts in  $T_w - T_{sat}$  (for a fixed heat-transfer rate) of only a maximum of  $5^{\circ}\text{F}$  as gravity was increased to  $20\text{ g}_n$ . The largest shifts were at low heat fluxes where the heat was being transferred partly by free convection. The direction of the shift changed from lower to higher temperature differences as the heat flux increased. More recent data for boiling of liquid hydrogen (ref. 8) have also demonstrated the insensitivity of nucleate boiling to increases in gravity. Additional information on gravity effects in boiling along with some discussion of the forces acting on the bubbles is given in reference 9.

To provide a better understanding of the nucleate-boiling mechanism in reduced gravity, the present authors studied the forces acting on single bubbles forming on a horizontal plate (refs. 10 and 11). For distilled water, the detachment of bubbles was found to be governed by a balance of buoyancy and surface-tension forces with the inertial force being very small. Hence, the inertial force was of little significance in accounting for the nucleate-boiling behavior in water at low gravity. It was observed that, at low gravity, there was a substantial increase in bubble coalescences, because the vapor tends to linger near the surface for an appreciable period after detachment. The new bubbles growing on the surface collide with this lingering vapor mass, and surface tension then pulls the bubbles into the vapor mass. This increased amount of coalescence greatly aids the removal of vapor from the surface.

For nucleate boiling in a 60-percent-by-weight aqueous sucrose solution (ref. 11), the bubbles forming on a horizontal plate grew much more rapidly than in distilled water. This rapid growth produced large inertial forces, which apparently accounted for the bubbles appearing to be propelled from the surface. As a result, for this fluid, the undisturbed bubbles leaving the surface were essentially the same size for both Earth and reduced gravities. As expected, in reduced gravity the detached bubbles tended to remain clustered near the heating surface for a much longer period of time.

To supplement these studies of bubble dynamics from a heated horizontal plate, the authors, in this investigation, have obtained heat-transfer data from a thin electrically heated wire. Because the wire has a low heat capacity, its temperature can respond rapidly to gravity changes, whereas the heated horizontal plate in references 10 and 11 had a large thermal mass and remained essentially at a fixed temperature when gravity was reduced. Data were obtained for nucleate boiling of water, ethyl alcohol, and 60-percent-by-weight aqueous sucrose solution for wires in both horizontal and vertical orientations. High-speed motion pictures were taken during all of the tests to aid in the interpretation of the boiling mechanisms.

Results were also obtained for film boiling of ethyl alcohol from horizontal and vertical wires. The vapor pattern observed for the horizontal wire is interpreted with regard to results derived from the Taylor instability theory, which has been previously applied in the literature to the film-boiling mechanism.

Little information exists on film boiling for gravity fields other than Earth gravity. In reference 12, the effect of increased gravity on film boil-

ing from a 3/16-inch horizontal tube is investigated. For the range tested, which was up to 7  $g_n$ , the hydrodynamic measurements of the bubble configurations agreed reasonably well with the theory based on the Taylor instability theory. Additional high-gravity results up to 22  $g_n$  are given in reference 13. In reference 1, a few photographs of film boiling in the reduced-gravity range are given for a heated horizontal tube. Heat-transfer data for film boiling from a sphere in the reduced gravity range are given in reference 4, where the Nusselt number was proportional to  $g^{1/3}$  in the range tested (0.01 to 1  $g_n$ ).

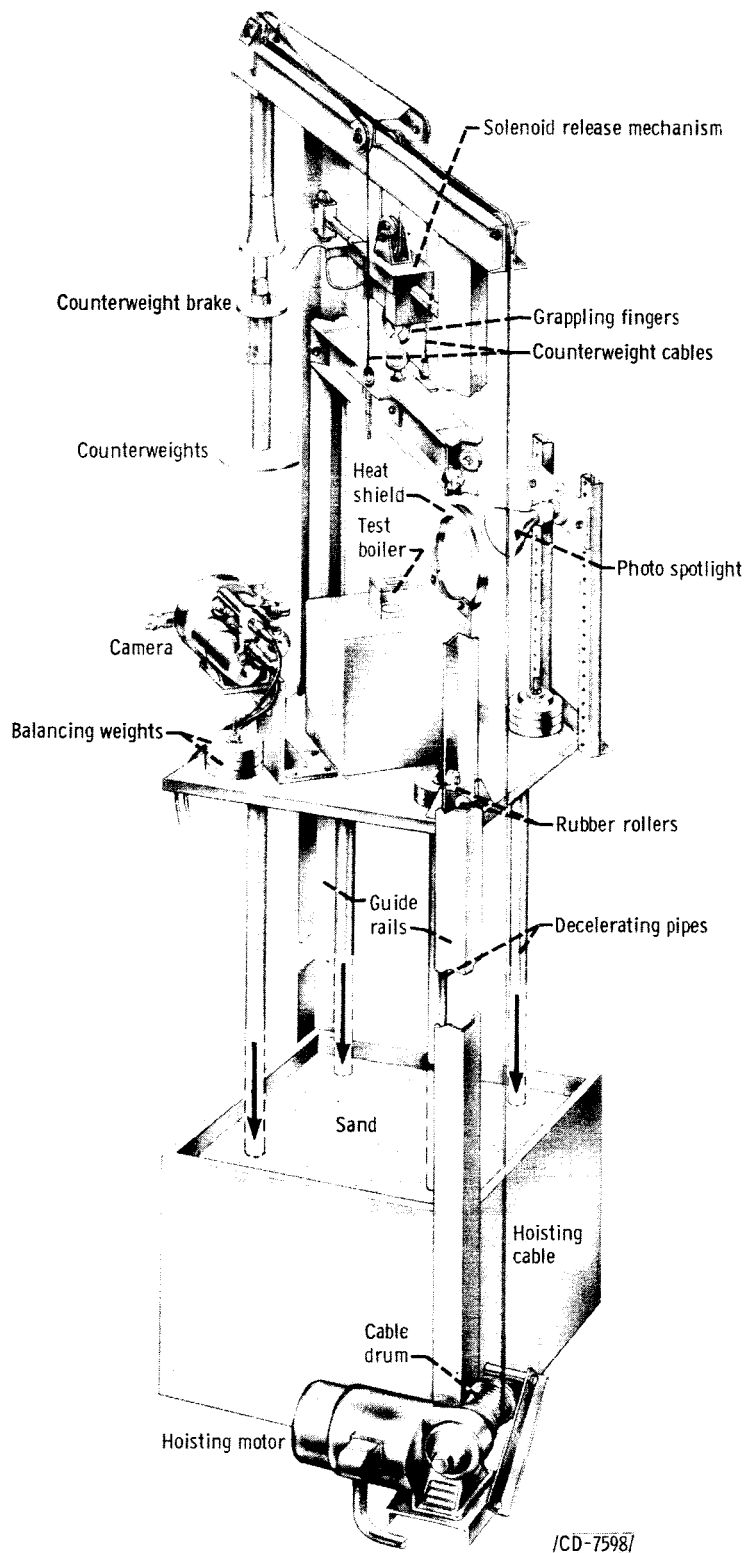
This report is concerned with film boiling from a heated wire 0.0197 inch in diameter. The configuration of the vapor surrounding the wire was greatly influenced by the large circumferential curvature (small radius) of the wire. When either a thin film of vapor or liquid covers a thin wire, or a liquid is formed into a thin thread, the circumferential curvature produces a surface-tension force that pulls the film or thread into a series of equally spaced spherical masses. This occurs because the volume of the film can be contained in such masses with less surface energy than that required for the cylindrical form. The instability of a cylindrical fluid element is considered in references 14 to 16. This type of instability should govern the vapor film surrounding a wire, if the wire radius is sufficiently small. For a larger diameter wire, the effects of gravity and circumferential curvature would be combined to influence the shape of the vapor film. These combined effects have recently been considered for a liquid film on a cylinder (ref. 17) and for a vapor layer surrounding a wire (ref. 18). These authors apparently were not aware of the relation of their problem to the problems in references 14 and 15. The effect of test-section diameter on film boiling from a horizontal cylinder has been reported in reference 19.

The results of the present investigation show that the circumferential curvature effects have an increasing influence on the vapor hydrodynamics as gravity is reduced. At zero gravity, this effect would prevent the vapor film from growing in a cylindrical configuration about the heated wire. For a vertical wire in film boiling, the effect of the vertical orientation becomes less significant as gravity is reduced. For very low gravity fields, the vapor orientation about the vertical wire becomes the same as that for a horizontal wire. A motion-picture film supplement C-238 that illustrates the foregoing results has been prepared and is available on loan. A request card and a description of the film are included at the back of this report.

## EXPERIMENTAL APPARATUS

### Counterweighted Drop Tower

A drop tower (fig. 1(a)) with a vertical fall of 12.5 feet was used to obtain reduced gravity fields. Counterweights of different mass were used to regulate the platform rate of descent in order to produce various effective gravity fields in the test boiler. Because of friction in the platform guides, the minimum gravity field obtained was 0.014 times Earth gravity. The test times were of the order of 1 second. Additional details, such as a description



(a) Counterweighted drop tower. (Drop height, 12.5 ft.)

Figure 1. - Experimental apparatus.

of the calibration of the tower to determine gravity field as a function of counterweight mass, are discussed in reference 10.

### Test Boiler

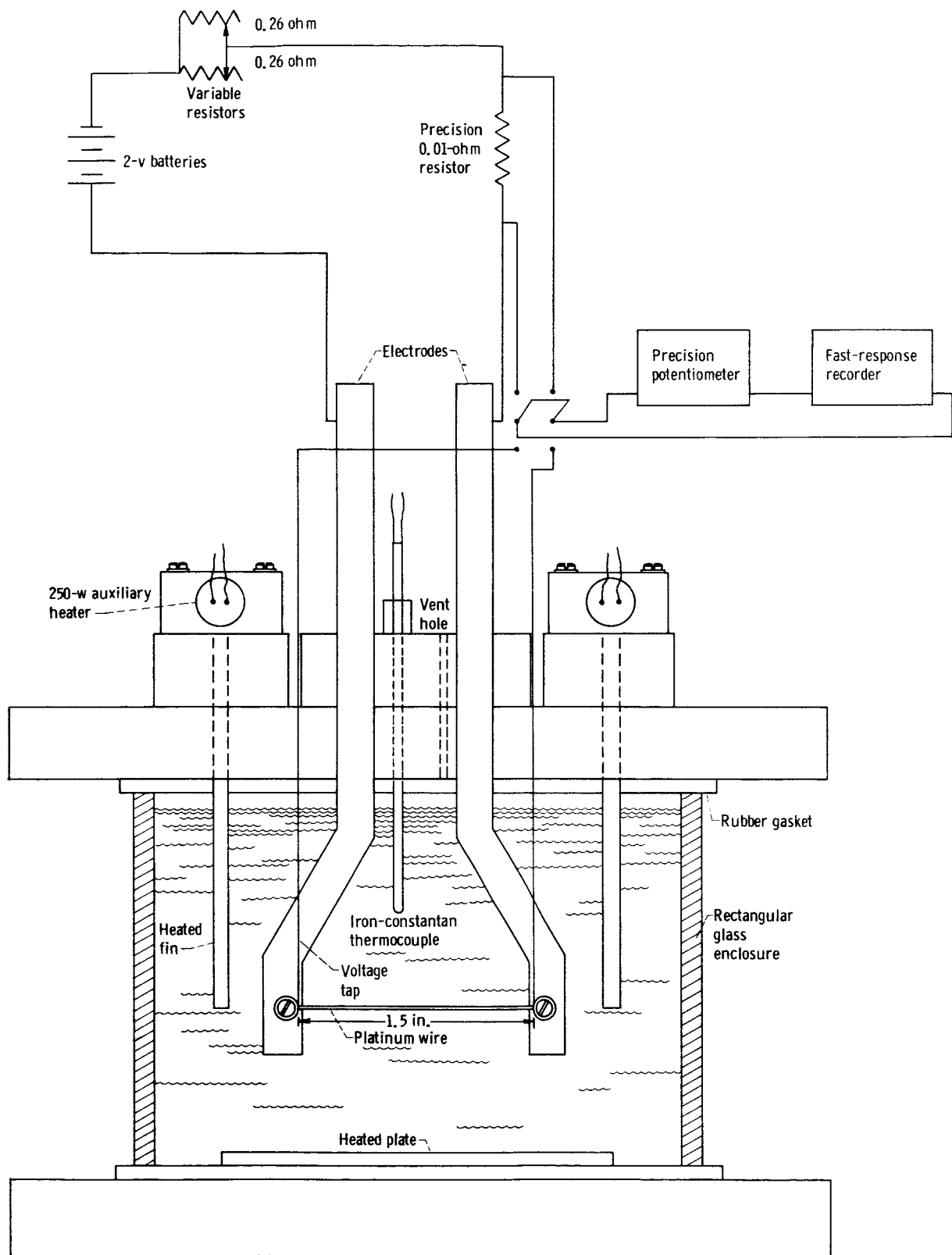
A platinum wire, 1.5 inches long and 0.0197 inch in diameter, was mounted between two copper electrodes suspended in the test liquid (see fig. 1(b)). A horizontal wire position is shown, but by inserting extensions onto the electrodes, a vertical orientation could also be obtained. The liquid was maintained at its saturation temperature by auxiliary heaters. Two heated fins extended down near the sides of the glass enclosure and supplied most of the auxiliary heating. A small amount of heat was also added by a plate at the bottom of the enclosure.

### Instrumentation

Electrical heating was supplied to the test wire by a parallel bank of six heavy-duty 2-volt batteries, each rated at 135 ampere-hours for a 1-hour discharge. The change in voltage when drawing 75 amperes from a battery for 10 minutes is only about 1 millivolt. Hence, during the test runs the circuit voltage remained very nearly constant, and the power to the test section did not drift as a result of the batteries having been partially discharged. Power to the test section was varied by means of two resistance elements connected in parallel and placed in series with the wire. The resistance elements each had a maximum resistance of 0.26 ohm and could be varied from 0 to 0.26 ohm by means of sliding contacts. Constantan, which has a low-temperature coefficient of resistance, was used in these elements to prevent the resistance of the circuit from changing if these resistors became warm from electrical dissipation.

The current in the circuit was obtained by measuring the voltage across a 0.01-ohm precision resistor in series with the heated wire. Voltage taps across the test wire permitted measurements of the wire voltage. From these two measurements, the heat dissipation from the wire and the wire resistance were computed. The wire resistance gave the average temperature of the wire (Temperatures mentioned hereinafter are understood to be average values over the wire length.), as the platinum test wires had been calibrated as resistance thermometers. For steady-state measurements at normal gravity, both of the preceding measurements were obtained with a precision potentiometer readable to 0.01 millivolt for readings above 0.161 volt and to 0.001 millivolt for smaller values.

During the period of reduced gravity, only the changes from the normal-gravity signals were measured. This technique yields results having much better accuracy than those obtained by measuring the current and voltage during the reduced-gravity period and then subtracting the normal-gravity readings to determine the small change. Measuring only the change of signals was accomplished by placing a fast-response recording potentiometer in series with the precision potentiometer connected to either the voltage or current signal, as shown in figure 1(b). The precision potentiometer was then adjusted to give a



(b) Test boiler with test wire (shown in horizontal orientation) and instrumentation.

Figure 1. - Concluded. Experimental apparatus.

signal equal and opposite to that present in Earth gravity. Hence, during the drop, only the difference from the original normal-gravity condition was measured.

The pen on the recording potentiometer had a  $1/8$ -second response for a full-scale travel of  $4\frac{1}{2}$  inches. Several voltage ranges were available (e.g., 0 to 1, 0 to 5, 0 to 10, and 0 to 50 mv). For the test wires used, a change in voltage of 1 millivolt across the wire corresponded approximately to a temperature change of  $2^{\circ}$  F, and consequently the instrumentation was capable of detecting wire temperature changes of a fraction of a degree that resulted from the gravity reduction. Chart speeds up to 6 inches per second were available.

The fluid temperature in the boiler was measured by two iron-constantan thermocouples, each encased in a stainless-steel sheath, as illustrated in figure 1(b).

Motion pictures at about 3500 frames per second were obtained by a high-speed 16-millimeter camera. The camera was started a fraction of a second before the test platform was dropped so that each film roll provided a direct comparison between the normal-gravity condition and the reduced-gravity condition immediately following.

#### PROCEDURE

The boiler was carefully cleaned, and the test section was wiped with acetone. The fluid was brought to its saturation temperature by the auxiliary heaters and allowed to boil for about 1 hour in order to drive off dissolved gases. The variable resistors were adjusted to provide the desired test-wire heat flux. The battery circuit was then energized, and the fluid was allowed to boil from the wire until the current and voltage readings were steady. The platform was raised to the dropping position, and the counterweight was adjusted to provide the desired gravity field. The camera was then started, and after about 0.3 second the platform was automatically released. The camera speed was such that shortly before the end of the 100-foot roll of film had been reached, the platform was decelerated by contacting a sand bed. During the reduced-gravity period, a measurement of either the voltage change across the wire or across the precision resistor was obtained on the recorder. The conditions during the reduced-gravity periods were very reproducible so the procedure was then repeated to obtain the other voltage change. Steady-state readings at normal gravity were made, and the drop tests and steady-state readings were repeated as a check. This procedure was followed for each gravity field and each heat flux.

#### NUCLEATE-BOILING DATA

For nucleate boiling, the reduced-gravity tests were made only at the lowest gravity field attainable, which was  $0.014 g_n$ . The tests were all performed with saturated liquid at atmospheric pressure.

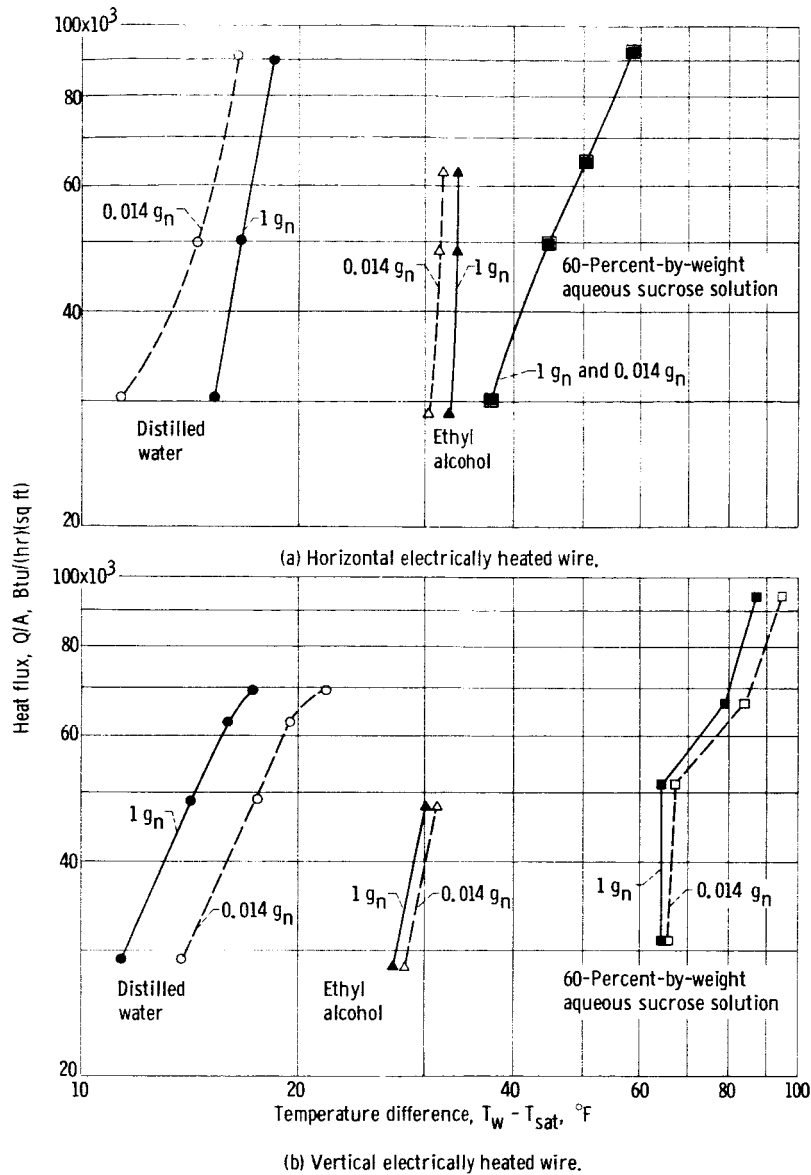


Figure 2. - Nucleate boiling curves for Earth gravity and 0.014 Earth gravity.

The steady-state wire resistance gave the average wire temperature. Since the wire was being heated internally, the surface temperature was lower than the measured average temperature over the wire cross section. A corrected surface temperature was obtained from the following expression given in reference 20:

$$T_w = T_{av} - \frac{\frac{Q}{A} D}{8k} \quad (1)$$

This correction was applied to both the normal- and the reduced-gravity measurements and generally amounted to a few degrees. There is also an axial tem-

TABLE I. - HEAT-TRANSFER DATA FOR NUCLEATE BOILING FROM ELECTRICALLY HEATED WIRE

Liquid	Horizontal wire				Vertical wire			
	Earth gravity, 1 $g_n$		Reduced gravity, 0.014 $g_n$		Earth gravity, 1 $g_n$		Reduced gravity, 0.014 $g_n$	
	Heat flux, $Q/A$ , Btu/(hr)(sq ft)	Temper- ature differ- ence, $T_w - T_{sat}$	Heat flux, $Q/A$ , Btu/(hr)(sq ft)	Temper- ature differ- ence, $T_w - T_{sat}$	Heat flux, $Q/A$ , Btu/(hr)(sq ft)	Temper- ature differ- ence, $T_w - T_{sat}$	Heat flux, $Q/A$ , Btu/(hr)(sq ft)	Temper- ature differ- ence, $T_w - T_{sat}$
Distilled water	30,300 50,100 90,700	15.3 16.7 18.5	30,200 50,000 90,600	11.3 14.5 16.5	29,100 48,700 62,800 69,400	11.3 14.2 15.9 17.3	29,100 48,900 62,900 69,700	13.8 17.6 19.5 21.8
Ethyl alcohol	28,700 48,300 62,500	32.2 33.1 33.1	28,700 48,200 62,500	30.2 31.3 31.9	28,300 47,800	27.1 30.1	28,300 47,800	28.2 31.2
60-Percent- by-weight aqueous sucrose solution	30,000 49,900 64,700 92,100	37.3 44.9 50.3 58.4	30,000 49,900 64,700 92,100	37.3 44.9 50.3 58.4	31,000 51,200 68,200 93,800	64.3 64.1 79.0 87.1	31,000 51,400 66,400 94,000	65.8 67.1 83.9 94.5

perature variation resulting from heat conduction along the wire to the cooler supporting electrodes. The magnitude of this effect was determined by using the results given in reference 21 (p. 152) and was negligible for the present experimental conditions; therefore, no correction was applied. From the change of wire voltage and current flow during reduced gravity, the change of resistance was determined. By using the temperature coefficient of resistance, which was known from previously calibrating the wires, the change in wire temperature was determined. The voltage signal recorded during the reduced-gravity period resembled a square wave. After the platform was released, the signal would shift very rapidly to a new value and then remain at that value until the platform was decelerated, which would cause the signal to return to its original value.

#### Results for Horizontal Wire

Data were obtained for distilled water, 60 percent-by-weight aqueous sucrose solution, and ethyl alcohol for wires in both horizontal and vertical positions. The heat-transfer results are shown in figure 2 and are listed in table I. For the horizontal wire, the  $Q/A$  against  $\Delta T$  curves for water and ethyl alcohol have shifted to the left for the low-gravity condition. This displacement of the curves indicates that, at low gravity and for a given heat flux, a smaller thermal driving force ( $\Delta T$ ) is required. Hence, the boiling process appears to have become more efficient with the gravity reduction. This agrees with the results for water in reference 5. The curve shift, however, is small (of the order of a few degrees), which would be of little consequence in an engineering application. For the sucrose solution, no shift was noted and, hence, the nucleate-boiling process in a sucrose solution appears to be insensitive to gravity.

A possible explanation for the foregoing behavior may be obtained by examining the photographic results presented herein and considering the results in references 10 and 11, which investigated nucleate-boiling bubble dynamics and the forces acting on bubbles in reduced gravity. Some typical photographs



of nucleate boiling from a horizontal wire at a heat flux of approximately 50,000 Btu per hour per square foot in Earth gravity and for  $0.014 g_n$  are shown in figure 3 for three fluids. Each set gives the normal-gravity condition and three reduced-gravity pictures for successively later times. The photographs all indicate the same general behavior. For normal gravity, there are distinct nucleation sites spaced along the wire so that most of the wire is not covered by vapor and the liquid does not have any difficulty flowing in toward the surface around the departing bubbles. The bubbles in ethyl alcohol are characteristically smaller and more numerous than those in water or the sucrose solution. When the gravity field is reduced, the bubbles begin to coalesce to a much greater extent, and a group of larger bubbles is formed. As the time is increased, more coalescences occur, and a pattern is formed with small bubbles near the wire and bubbles of increasing size at larger distances from the wire. It is also important to note that the bubbles are tangent to the wire and do not tend to grow around it. At the end of the low-gravity period most of the wire is still not covered by vapor, and it appears that sufficient space remains between the bubbles so that the liquid can flow in toward the wire.

In references 10 and 11, boiling occurred from a flat horizontal surface, and hence the nucleation mechanism may have been different from that occurring from a wire; however, some of the qualitative results are believed applicable to the present study. In reference 11 the forces acting on a bubble during its growth and departure were analyzed by using measurements obtained from photographic data. For sucrose solutions it was observed that bubble departure diameters were independent of gravity. The analysis of forces indicated that departure was caused primarily by the relatively large inertial forces developed during the characteristic rapid growth of bubbles in a sucrose solution. Buoyancy forces were of little significance, and thus departure was governed primarily by the gravity-independent inertial force. Hence, the present results (macroscopic in nature), which indicate no change in the boiling curve with a change in gravity for sucrose solutions, are consistent with the corresponding results of reference 11 (microscopic in nature).

For water, the force analysis in reference 11 indicated that bubble departure for single undisturbed bubbles was primarily dependent on the buoyancy force overcoming the surface-tension force, the inertial force being of little significance. Since, for water, the bubble departure is gravity dependent, a poorer heat-transfer performance might be expected at low gravities as a result of vapor collecting and lingering near the heated surface. The photographic data of reference 10, however, revealed a bubble-coalescence mechanism that appeared to increase the turbulence and stirring action within the fluid near the heated surface. This increased activity would tend to improve the heat transfer. This coalescence mechanism consists of (1) the growth of a bubble and its eventual detachment from the surface, (2) the hovering of the detached bubble just above the surface, and (3) the subsequent rapid growth and coalescence with the hovering bubble of numerous small bubbles originating from the same nucleation site. Hence, the lingering of a bubble near the surface provided a means for removing several subsequent bubbles, thus compensating for the low buoyancy force, which by itself would produce poor bubble removal from the surface. This coalescence mechanism in low gravity may actually remove the bubbles



Figure 3. - Nucleate boiling for three fluids from horizontal electrically heated wire in Earth gravity and 0.014 Earth gravity.

at a more rapid rate than buoyancy alone does in normal gravity, thus providing a small increase in the boiling heat-transfer coefficient.

Another factor that may be significant in accounting for the observed change in temperature of the wire is that the downward-facing portion of the wire surface is utilized more efficiently in low gravity because the boiling becomes more symmetrically distributed about the wire as gravity is reduced.

The foregoing discussion and the heat-transfer data indicate that a means for removing bubbles from the wire is present even in a low-gravity field. The inertial force removes the bubbles in sucrose solutions, while coalescence with larger bubbles frequently removes the newly formed bubbles in water or ethyl alcohol. As more bubbles continue to coalesce, a pattern is formed that consists of small bubbles near the wire and larger bubbles away from the wire. With at least a small gravity field present to remove the larger bubbles, it appears that the liquid may continue to flow in under the bubbles thereby keeping the wire in contact with the liquid and sustaining nucleate boiling.

The results reported herein indicate that gravity reductions do not seriously alter the heat-transfer capabilities of a boiling system (at least for the short test times available and the fluids tested) and are in agreement with the results of references 1 to 5 as summarized in the INTRODUCTION.

#### Results for Vertical Wire

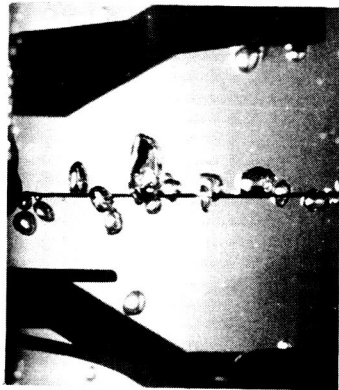
Nucleate-boiling data for the wire placed in a vertical position are shown in figure 2(b). For this orientation a reduction in gravity field to  $0.014 g_n$  shifts the boiling curve to the right, that is, in the direction of less efficient heat transfer, where, for a given heat flux, a higher temperature difference is required. This behavior is opposite that observed in the horizontal orientation. The reason for this difference is not apparent from the photographic results because the bubble-removal mechanism strongly resembles that for the horizontal wire.

For the vertical orientation it was necessary to operate at lower heat fluxes than those used for the horizontally oriented wire in order to prevent transition from nucleate to film boiling during the low-gravity period. Perhaps in the vertical case the bubbles tend to rise more closely along the wire surface, which increases the tendency for the transition to film boiling to occur.

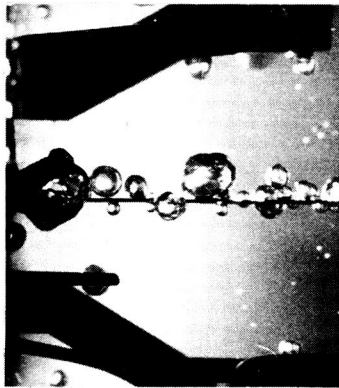
Photographs of nucleate boiling from a vertical wire for three fluids in Earth gravity and  $0.014 g_n$  are shown in figures 4(a) and (b). The heat fluxes are close to those in figure 3, which permit direct comparisons to be made. In Earth gravity the bubbles are clustered about the wire. For boiling alcohol the bubbles are small and so numerous that the wire is hidden by them, while for boiling water much of the wire is visible between isolated nucleation sites. For the reduced-gravity field of  $0.014 g_n$ , the buoyancy force on a bubble becomes very small, and the bubble configuration changes with time in a manner similar to that for the horizontal wire. During the test time available, the bubble pattern did not achieve a steady configuration, and bubbles

Water

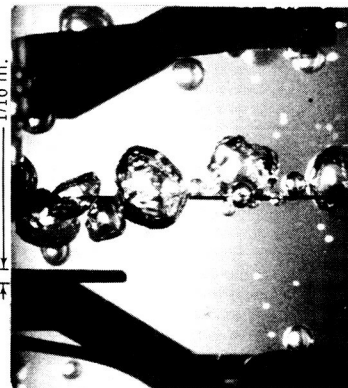
Heat flux,  $Q/A$ , Btu/(hr)(sq ft): 48,700  
 Temperature difference,  $\Delta T$ , °F: 14.2



Heat flux,  $Q/A$ , Btu/(hr)(sq ft): 48,900  
 Temperature difference,  $\Delta T$ , °F: 17.6



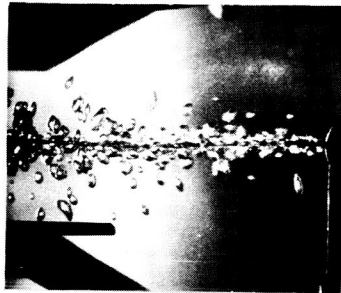
Time from beginning of reduced-gravity period, sec: 0.05



0.20

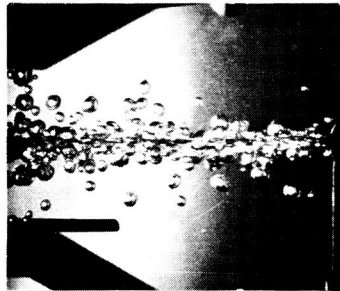
Alcohol

47,800  
 30.1

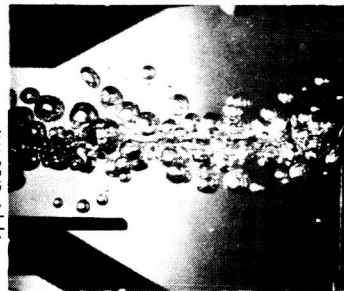


(a) Earth gravity.

47,800  
 31.2



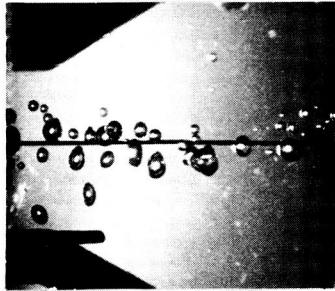
0.05



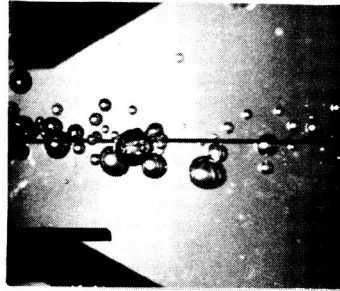
0.20

60-Percent-by-weight  
 aqueous sucrose solution

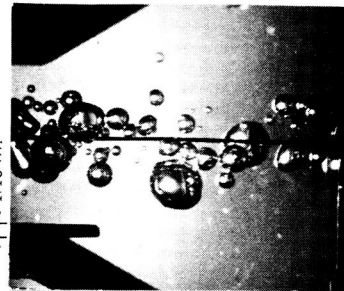
51,200  
 64.1



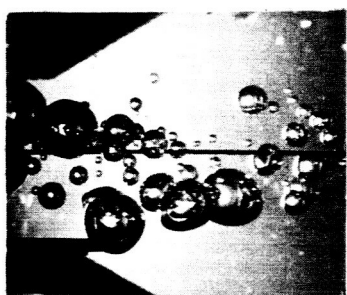
51,400  
 67.1



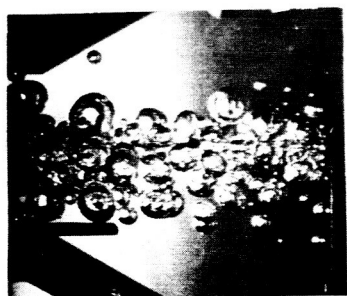
0.05



0.20

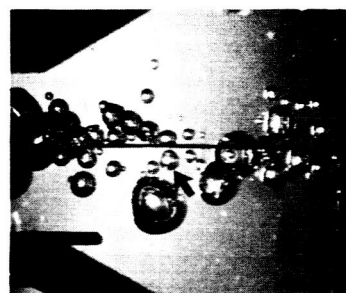


0.50

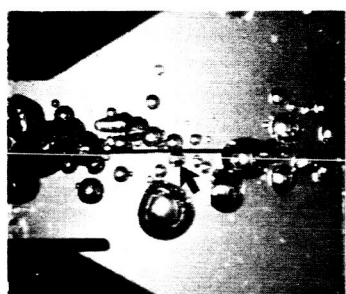


0.50

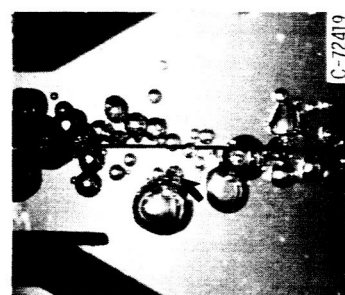
(b) 0.014 Earth gravity.



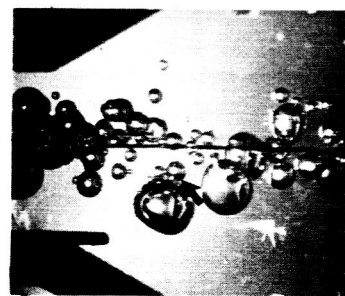
0.005



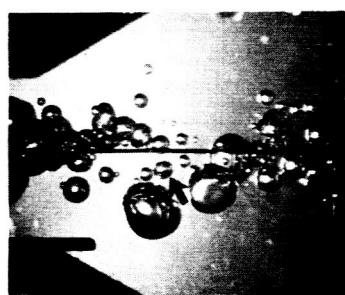
Time from bubble  
departure, sec; 0



0.023



0.017



0.010

(c) Bubble being propelled horizontally from vertical wire in reduced-gravity (0.014  $g_n$ ) boiling of 60-percent-by-weight aqueous sucrose solution. Heat flux,  $Q/A$ , 51,400 Btu per hour per square foot; temperature difference,  $\Delta T$ , 67.1° F.

Figure 4. - Nucleate boiling from vertical electrically heated wire.

were still continuing to coalesce into larger masses. At the end of the test period, it appeared that the fluid was still able to flow in underneath the bubbles and wet the wire while the bubbles remained tangent to the wire. The bubbles were not observed to envelop the wire and rise along it, thereby coalescing with additional bubbles to form a vapor film; hence, during the test period nucleate boiling continued. It would be desirable to have much longer testing times so that a steady bubble configuration could be achieved.

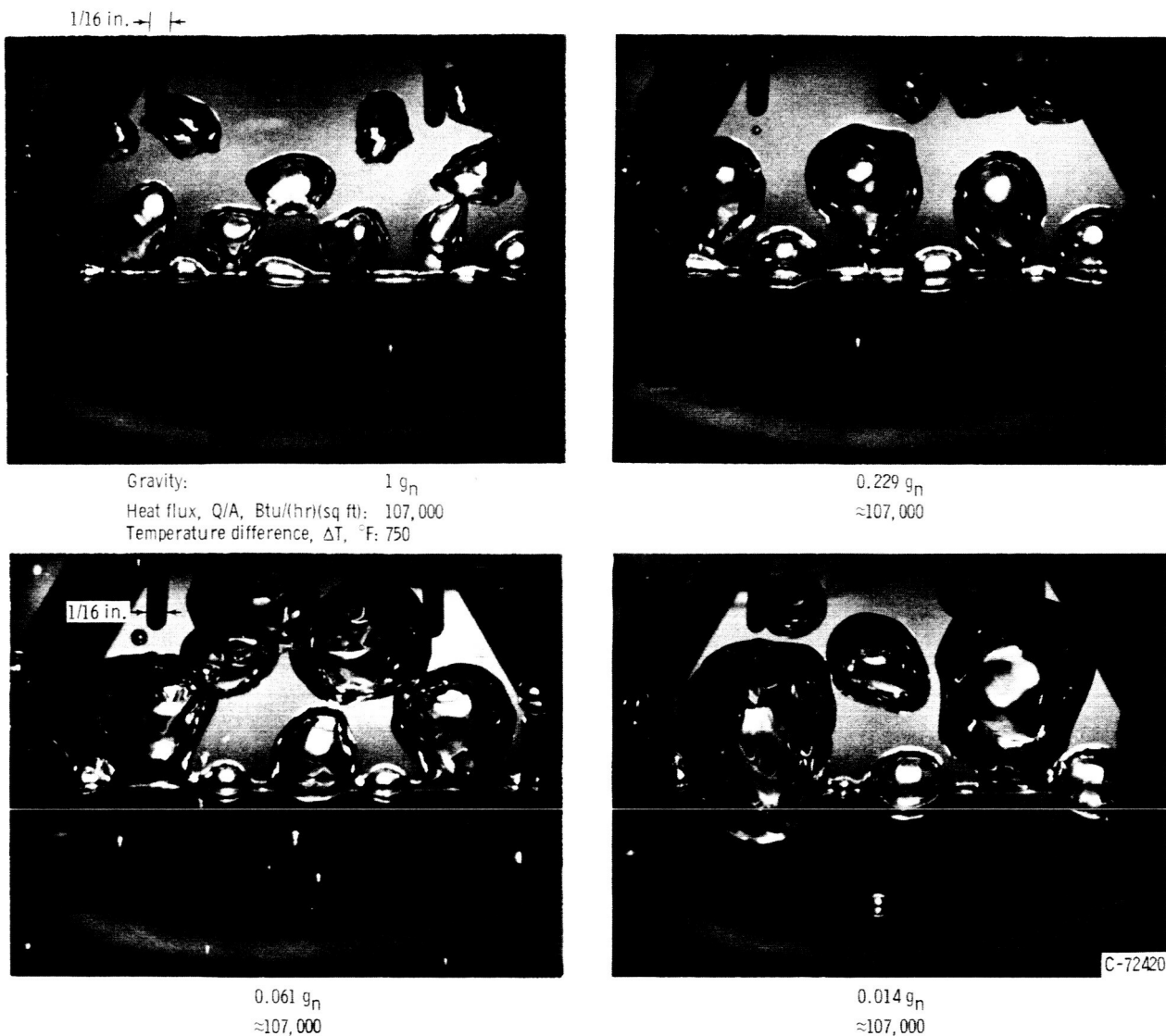
The inertial forces that develop during the growth of bubbles in sucrose solution are demonstrated quite well by the boiling that occurred from a vertical wire in low gravity (fig. 4(b)). In this instance, bubbles are propelled horizontally from the heated surface, as illustrated by the sequence in figure 4(c). A bubble (indicated by arrow) moves horizontally off the surface and eventually coalesces with a larger bubble away from the surface.

#### FILM-BOILING DATA

Film boiling was studied for both horizontal and vertical wires at various reduced-gravity fields. Ethyl alcohol was selected because, for this fluid, film boiling occurs at temperatures sufficiently moderate to prevent the wire from melting. In contrast with nucleate boiling, the change in surface temperature in the film-boiling regime is considerable (of the order of a few hundred degrees) when the wire is subjected to low gravity (as has been demonstrated in ref. 4). For the short duration of the present tests the recorded voltage and current signals indicated a rapid temperature increase of the order of  $100^{\circ}\text{F}$  during the test, but the test time was too short for a steady surface temperature to be achieved. Hence, data for heat flux as a function of temperature difference for reduced gravities could not be obtained for the film-boiling regime. The test results regarding the hydrodynamics of film boiling as a function of gravity were quite interesting and are reported and discussed in the subsequent sections. Even though the surface temperature had not reached a steady condition, the vapor pattern adjusted almost instantaneously to the reduced-gravity conditions and then maintained the same pattern throughout the remainder of the test. The vapor pattern was evidently a much stronger function of gravity than of surface temperature.

Typical photographs of film boiling for several gravity fields are shown in figures 5 and 6, for horizontal and vertical wires, respectively. The photographs indicate that, as gravity is reduced, there is a general increase in the size of the periodically spaced vapor masses along the wire. The vertical wire is especially interesting because the vapor does not rise in the form of a smooth boundary layer of increasing thickness around the wire. Rather, the circumferential surface tension pulls the vapor into a series of regularly spaced bubbles rising along the wire. When gravity becomes low, the influence of buoyancy, and hence wire orientation, is greatly reduced, and the vapor configuration around the vertical wire achieves an appearance similar to that for the horizontal wire. The principal difference is that, for the vertical wire, the entire vapor configuration moves axially along the wire.

In order to understand the hydrodynamic results better, the instability theory will be considered for film boiling from a horizontal cylinder.



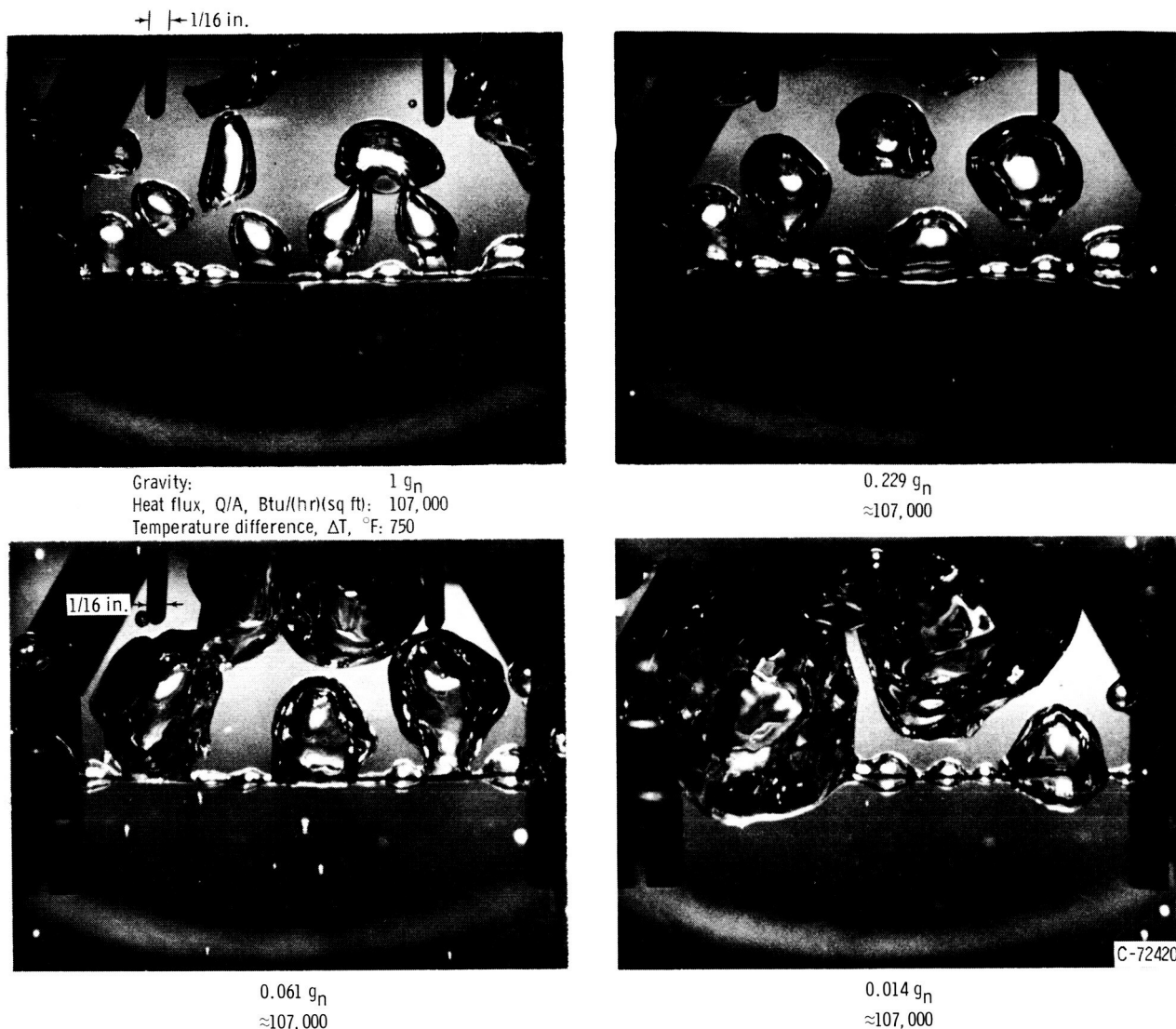
(a) Configurations of regularly spaced vapor masses.

Figure 5. - Film boiling of ethyl alcohol from horizontal electrically heated wire at Earth and three reduced gravities.

### Instability Theory for Film Boiling on Horizontal Wire

Consider a heated wire of finite length  $L$  surrounded by a vapor film as shown in figure 7(a) (p. 21). Along the upper portion of the wire the liquid lies above the vapor, and as a result the interface is unstable. A series of regular waves is formed as has been analyzed in reference 22. The waviness of the interface is of interest because it is related to the regular release of bubbles in film boiling, and equations for the heat transfer have been formulated by utilizing the instability theory. Taylor's analysis, in which a plane interface was considered, has been extended to a cylindrical interface (refs. 17 and 18). Fluid dripping from a horizontal cylinder was investigated, in reference 17, and the film-boiling configuration was studied in reference 18. In appendix B the theory is reviewed and modified in order to adapt it to a wire





(b) Configurations of minimum wavelength disturbances.

Figure 5. - Concluded. Film boiling of ethyl alcohol from horizontal electrically heated wire at Earth and three reduced gravities.

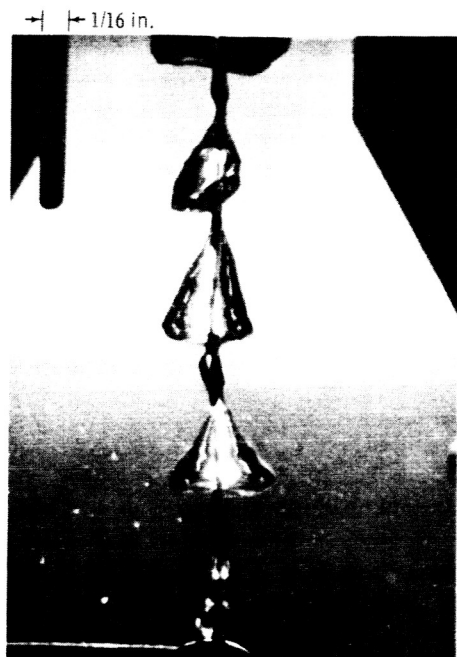
of finite length that is undergoing film boiling in reduced gravity. The important results will now be briefly summarized in order to compare them with the film-boiling bubble configurations observed in reduced gravity.

In the instability theory, the vapor layer is assumed to be disturbed by a small perturbation  $\eta$  having a sinusoidal shape about a smooth equilibrium interface position:

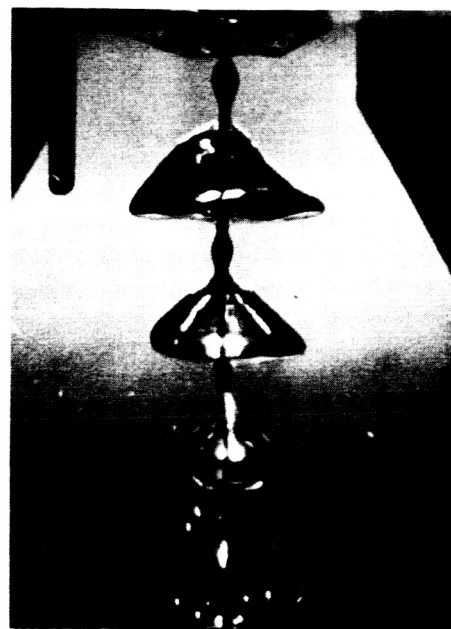
$$\eta(x, \tau) = (2m + 1) \frac{\pi}{L} \frac{C_1}{n} e^{n\tau} \sin(2m + 1) \frac{\pi x}{L} \quad (2)$$

The wave shape that has the greatest probability of being observed physically is the one for which this perturbation will grow most rapidly. This most

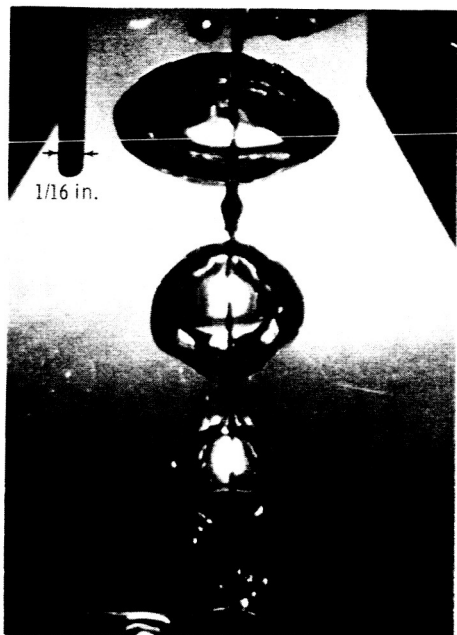




Gravity:  $1 g_n$   
 Heat flux,  $Q/A$ , Btu/(hr)(sq ft): 65,300  
 Temperature difference,  $\Delta T$ , °F: 690



$0.229 g_n$   
 $\approx 65,300$



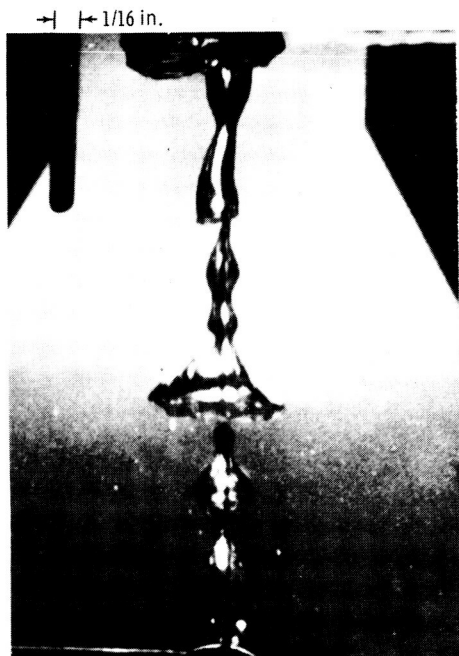
$0.061 g_n$   
 $\approx 65,300$



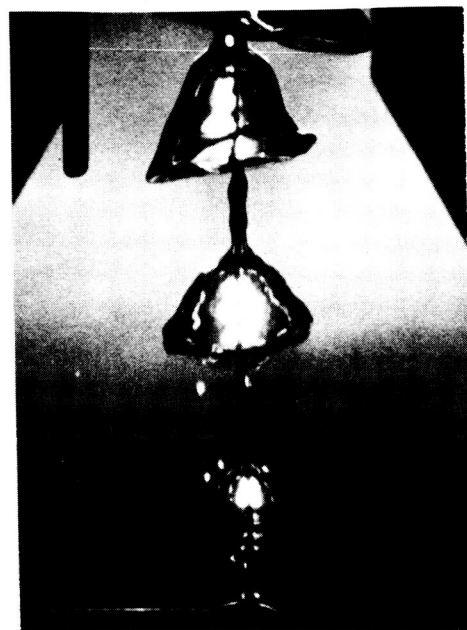
$0.014 g_n$   
 $\approx 65,300$

(a) Configurations of regularly spaced vapor masses.

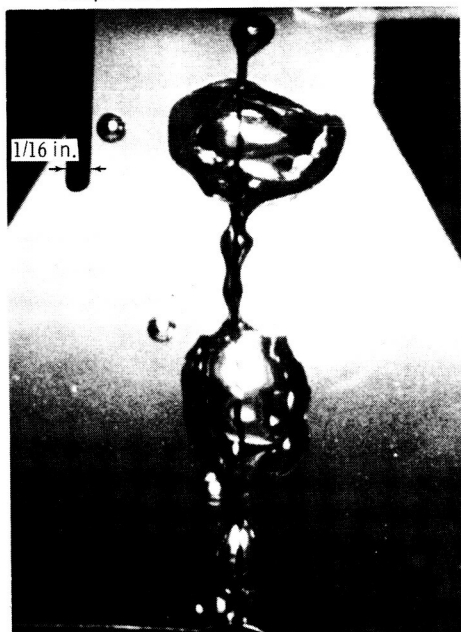
Figure 6. - Film boiling of ethyl alcohol from vertical electrically heated wire at Earth and three reduced gravities.



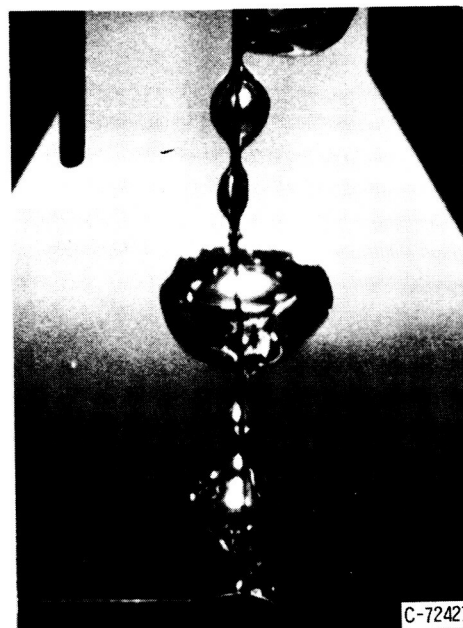
Gravity:  $1 g_n$   
 Heat flux,  $Q/A$ , Btu/(hr)(sq ft): 65,300  
 Temperature difference,  $\Delta T$ , °F: 690



$0.229 g_n$   
 $\approx 65,300$



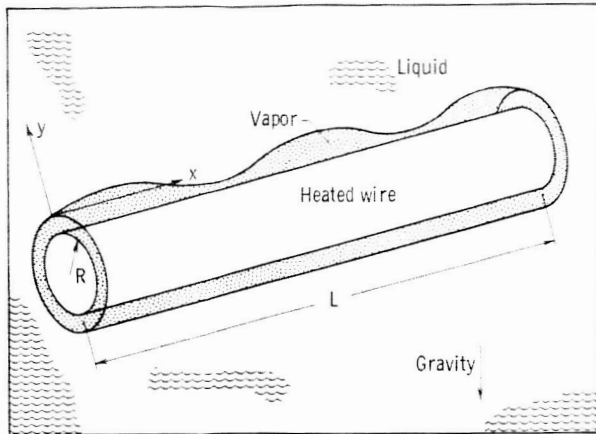
$0.061 g_n$   
 $\approx 65,300$



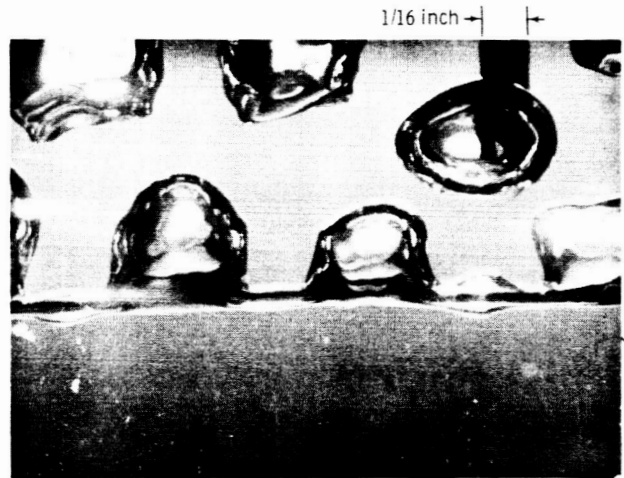
$0.014 g_n$   
 $\approx 65,300$

(b) Configurations of minimum wavelength disturbances.

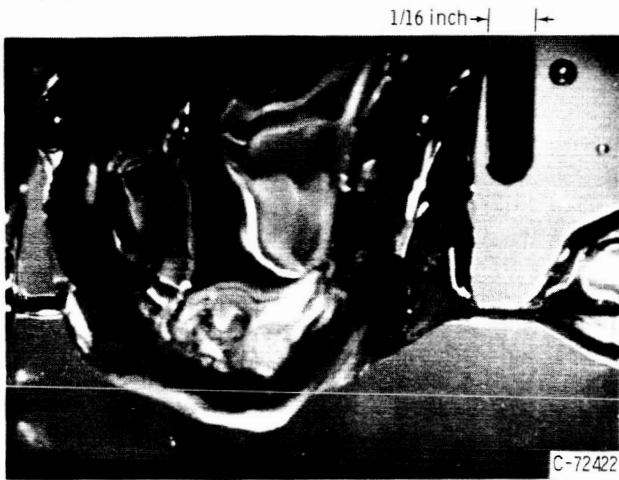
Figure 6. - Concluded. Film boiling of ethyl alcohol from vertical electrically heated wire at Earth and three reduced gravities.



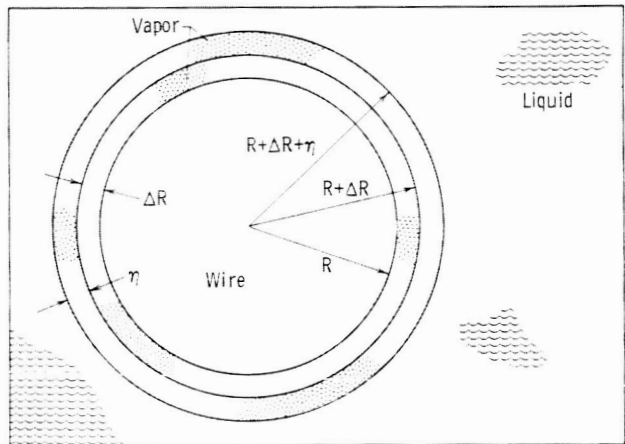
(a) Schematic drawing and coordinate system of slightly perturbed vapor layer.



(b) Minimum thickness configuration of vapor layer. Heat flux, 102,000 Btu per hour per square foot; temperature difference, 675° F. Earth gravity.



(c) Minimum thickness configuration of vapor layer. Heat flux,  $\approx 102,000$  Btu per hour per square foot. 0.014 Earth gravity.



(d) Coordinates in cross section of wire and vapor layer.

Figure 7. - Film-boiling vapor configuration on electrically heated horizontal wire.

unstable or "most dangerous" condition corresponds to a specific value  $m_d$  of the integer  $m$ , and is given by the expression (see appendix B for details of development)

$$m_d = -\frac{1}{2} + \frac{L}{2\sqrt{3}\pi} \left[ \frac{g}{\sigma} (\rho_l - \rho_v) + \frac{1}{(R + \Delta R)^2} \right]^{1/2} \quad (3)$$

where  $\Delta R$  is the average thickness of the vapor layer. The thickness  $\Delta R$  has been assumed uniform in the analysis in appendix B, this assumption being based on the photographs in figures 7(b) and (c).

Corresponding to  $m_d$ , the most dangerous wavelength is given by

$$\lambda_d = \frac{2L}{2m_d + 1} = 2\sqrt{3} \pi \left[ \frac{g}{\sigma} (\rho_l - \rho_v) + \frac{1}{(R + \Delta R)^2} \right]^{-1/2} \quad (4)$$

For a very large wire radius  $R$ , the second term in the square root vanishes, and the expression reduces to that for an instability on a flat plate. The second term thus accounts for the effect of cylindrical curvature. This term will dominate when  $R$  becomes sufficiently small.

### Interpretation of Experimental Data

Consider film boiling of ethyl alcohol with the fluid properties for boiling at atmospheric pressure as follows: the liquid density  $\rho_l$  is 45.75 pounds per cubic foot divided by Earth gravity  $g_n$ , the surface tension  $\sigma$  is  $10.16 \times 10^{-5}$  pound per inch, and the vapor density  $\rho_v$  is negligible compared with  $\rho_l$ . The radius of the experimental wire is 0.0099 inch. From the photographs, the vapor film thickness  $\Delta R$  was measured and was approximately 0.004 inch. Then for Earth gravity ( $g = g_n$ )  $\frac{g}{\sigma} (\rho_l - \rho_v) = 261$  per square inch and  $1/(R + \Delta R)^2 = 5180$  per square inch. This shows that, for the present conditions, the most dangerous unstable wavelength is strongly dependent on the second term in the square root in equation (4), which is the term arising from the circumferential curvature of the wire. For Earth gravity and a wire length  $L$  of 1.5 inches, equations (3) and (4) give  $m_d(1 g_n) \approx 10$  and  $\lambda_d(1 g_n) = 2L/(2m_d + 1) \approx 0.15$  inch. When the gravity field is reduced to zero these values become  $m_d(0 g_n) \approx 9$  and  $\lambda_d(0 g_n) \approx 0.16$  inch. Hence, because of the predominant effect of the circumferential curvature, the most dangerous wavelength is essentially insensitive to gravity in the gravity range less than or equal to Earth gravity.

The photographs in figure 5(a) (p. 17) show that the size of the regularly spaced vapor masses increase as gravity is reduced, and for low gravities they are spaced farther apart than the few tenths of an inch indicated by the computed most dangerous wavelength. The linearized theory, however, is restricted to only very small displacements of the vapor layer. Hence, to make a proper comparison with theory, a cylindrical portion of the layer must be observed that is just beginning to become unstable. Although this ideal configuration could not be obtained experimentally, the photographs in figures 5(b) and 6(b) show some adjacent unstable disturbances in regions where the film is thin. For these disturbances, the wavelengths are in the approximate range predicted by theory. These unstable disturbances were generally observed to collapse before growing very large; the vapor would flow axially into the adjacent large bubbles. Hence, the spacing of the large bubbles does not appear to be describable by the Taylor instability theory, which yields idealized results that do not account for the increased tendency of bubbles to merge as gravity is reduced.

The photographs herein show that even in low-gravity fields the vapor film can have unstable disturbance waves with short wavelengths (as indicated by the present analysis) that arise chiefly because of circumferential surface-tension

effects. These waves, which are predicted by instability theory, differ significantly from the actual configuration of large bubbles leaving the wire in reduced gravity. These large bubbles are formed by the merging of adjacent bubbles thereby obscuring the original wave pattern arising from instabilities. In reference 18 a regular wave behavior was readily observed for wire radii equal to or greater than 0.1 inch, but for smaller diameter wires the merging of adjacent bubbles became increasingly significant. The present results show that the merging is also greatly increased as gravity is reduced because of the poorer vapor removal. Hence, the gravity field plays a very significant role in the ultimate vapor configuration. Surface tension is also important as it acts to form the merged vapor into spherical shapes as shown quite well, for example, by the vertical configuration in figure 6(a) (p. 19).

#### Comments Regarding Critical (Burnout) Heat Flux

In the present experiments for nucleate boiling, it was observed that the heat fluxes had to be reduced to prevent film boiling from being initiated during the low-gravity portion of the test. This behavior was expected as shown by both previous data (ref. 1) and the theory for a horizontal plate. The theory indicates that the critical flux should decrease as  $g^{1/4}$ . The theory for the critical flux (ref. 23) is based on a Helmholtz instability in which an interference between the vapor leaving the surface and the liquid moving toward the surface occurs. The spacing of the opposing vapor and liquid streams is determined from the wavelength of the Taylor instability waves in the vapor layer. In the present case for a thin wire test section, equation (4) indicates that the wavelength of a disturbance is a function both of gravity and wire radius. At small radii and low gravity, the equation indicates that instabilities will occur primarily as a result of the large circumferential surface tension of the liquid film about the small wire. Since, according to reference 23, the critical heat flux is related to the instabilities, the separate effects of gravity reductions and wire diameter reductions on the critical flux will now be considered.

For a thin wire test section, as gravity is reduced, the  $1/R^2$  term in equation (4) becomes dominating, which indicates that the critical heat flux should eventually become independent of further gravity reductions. At the lowest gravities in figure 3 of reference 1, the critical heat flux did have a tendency to drop off less rapidly than  $g^{1/4}$  so that the circumferential surface tension may have had some effect. Equation (4), however, indicates that for the 0.0453-inch-diameter test section used in reference 1, the surface-tension effect ( $1/R^2$  term) should have been dominant. The fact that surface-tension effects were not strongly evident indicates that the Taylor instability theory, used in the present derivation, is not wholly suited for use in a model of film boiling from thin wires at low gravity.

Another aspect of this discussion is the consideration of film boiling in Earth gravity while the diameter of the horizontal heated wire is varied. If the Taylor instability theory is directly applicable, for small enough diameters the  $1/R^2$  term should become dominating compared with the  $\frac{g}{\sigma} (\rho_l - \rho_v)$  term, and the critical heat flux would then increase when  $R$  is reduced fur-

ther. This behavior has been observed only once in the literature, but was not explained by considering circumferential surface-tension effects. For wire diameters between 0.00075 and 0.002 inch it was observed that the critical heat flux increases with decreasing wire size (ref. 24). The explanation given was that the thin wire is mechanically weak, and the bubbles may be dislodged by vibrations resulting from the ebullition process. The authors of reference 25 expected that very small diameter horizontal heaters should be able to withstand higher critical heat fluxes than large diameter heaters. Their reasoning is that, for large diameter horizontal cylinders, liquid starvation is more quickly attained because it is more difficult for liquid to penetrate through the vapor layer to the top of the heater where burnout usually occurs. A review of the data of other investigators (fig. 9 of ref. 24) shows, however, that the critical heat flux has generally increased as the diameter of the horizontal wire is raised above approximately 0.004 inch. This trend indicates that the instability theory presented herein, which includes the influence of circumferential surface tension, is not directly applicable to the prediction of the critical heat flux.

#### CONCLUDING REMARKS

The effect of reduced gravity on nucleate and film boiling from an electrically heated wire has been studied experimentally for the horizontal and the vertical orientations. The boiling fluids, which were at saturation temperatures and atmospheric pressure, were water, ethyl alcohol, and 60-percent-by-weight aqueous sucrose solution.

For nucleate boiling at a fixed heat flux the average surface temperature of a horizontal wire became a few degrees cooler when gravity was reduced to 0.014 times Earth gravity for water and ethyl alcohol and did not change for the sucrose solution. For a vertical wire, the average surface temperature increased as much as several degrees for water, ethyl alcohol, and 60-percent-by-weight aqueous sucrose solution.

Since these changes were small, the tests indicated that heat removal by means of nucleate boiling was virtually insensitive to gravity reductions, at least for the gravities tested (1.0 to 0.014  $g_n$ ) and the short test times. Probable causes for this insensitivity are bubble coalescence, fluid inertia, and surface tension. These mechanisms provide a means for removing bubbles from the surface and thereby prevent the surface from becoming covered by a continuous vapor film.

For film boiling the vapor patterns observed for ethyl alcohol on horizontal and vertical wires changed significantly when the gravity field was reduced. The vapor bubbles leaving the wire increased in size, and, for the horizontal wire, the sideways coalescence of vapor masses became more frequent. For a vertical wire, the vapor did not rise in a smooth boundary-layer-like fashion about the wire, but rather, under the influence of surface tension, the vapor layer was broken into a series of regularly spaced bubble-like enlargements rising along the wire. This occurred even at normal gravity. As gravity was reduced, the vapor configuration for the vertical wire became similar to that for the horizontal wire.

Small unstable waves were observed on the thin vapor film surrounding the wire between the large vapor masses for both horizontal and vertical orientations in film boiling. For the 0.0197-inch-diameter wire used as a test section in the present experiments, circumferential surface tension dominated the behavior of these waves with gravity having an insignificant effect. This was revealed by analysis and demonstrated by experiment. The circumferential surface-tension effect kept the wavelength of these unstable waves from increasing appreciably when gravity became small.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, November 2, 1964.

# APPENDIX A

## SYMBOLS

$A$	area of heated surface
$C_1$	constant
$D$	wire diameter
$g$	gravitational field
$g_n$	Earth (normal) gravity
$k$	thermal conductivity of wire
$L$	length of wire
$m$	integer
$n$	exponential growth factor in eq. (2)
$p$	pressure
$Q$	heat transferred per unit time from solid surface to boiling liquid
$R$	wire radius
$\Delta R$	radial distance between wire surface and undisturbed position of vapor-liquid interface
$R_c$	radius of curvature of vapor interface in cross-sectional plane of heated wire (wire cross section is a circle)
$R_x$	radius of curvature of vapor interface in plane parallel to x-axis and passing through wire centerline
$T$	temperature
$\Delta T$	temperature difference, $T_w - T_{sat}$
$u$	velocity in x-direction
$v$	velocity in y-direction
$x$	axial distance along horizontal wire
$y$	vertical distance (parallel to gravitational acceleration) from top of undisturbed vapor-liquid interface surrounding horizontal wire
$\eta$	radial displacement of vapor-liquid interface from undisturbed position



$\lambda$	wavelength
$\rho$	density
$\sigma$	surface tension
$\tau$	time
$\Phi$	velocity potential function

Subscripts:

av	average
d	most dangerous disturbance
l	liquid
o	properties at undisturbed vapor-liquid interface
sat	saturation
v	vapor
w	surface

## APPENDIX B

### INSTABILITY THEORY FOR FILM BOILING ON HORIZONTAL WIRE

As shown in figure 7(a), a heated wire of length  $L$  is surrounded by a vapor film. The  $x$ -axis lies along the undisturbed liquid-vapor interface with the  $y$ -axis extending upward from the top of the interface. The velocity potential is defined as in the Taylor type of analysis (ref. 22 or 26):

$$u = - \frac{\partial \Phi}{\partial x} \quad v = - \frac{\partial \Phi}{\partial y} \quad (B1)$$

The continuity equation then becomes

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} = 0 \quad (B2)$$

so that any valid potential function must satisfy the Laplace equation. If an inviscid fluid is assumed, the linearized equation of motion for the vertical direction is

$$\frac{\partial v}{\partial \tau} + \frac{1}{\rho} \frac{\partial p}{\partial y} + g = 0 \quad (B3)$$

This equation is integrated with respect to  $y$ , which gives the result

$$- \frac{\partial \Phi}{\partial \tau} + \frac{1}{\rho} (p - p_0) + gy = 0 \quad (B4)$$

where  $p_0$  is the mean pressure at the interface for the unperturbed condition.

Writing and rearranging this equation for both the liquid and the vapor yield

$$p_l = p_{l,0} - g\rho_l y + \rho_l \frac{\partial \Phi_l}{\partial \tau} \quad (B5a)$$

$$p_v = p_{v,0} - g\rho_v y + \rho_v \frac{\partial \Phi_v}{\partial \tau} \quad (B5b)$$

The velocity potential functions in the liquid and the vapor can be chosen as

$$\Phi_l = C_1 e^{-(2m+1)(\pi/L)y} e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B6a)$$

$$\Phi_v = -C_1 e^{(2m+1)(\pi/L)y} e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B6b)$$

which both satisfy equation (B2). They also satisfy the conditions that the liquid and the vapor velocities are finite at large values of  $+y$  or  $-y$ , respectively, and that  $v_l = v_v$  at  $y = 0$ , which, for small displacements, is the approximate interface. The free boundary condition at the interface  $y = \eta(x, \tau)$  is

$$\frac{\partial \eta}{\partial \tau} = v(y \approx 0) = - \left. \frac{\partial \phi}{\partial y} \right|_{y=0} = (2m+1) \frac{\pi}{L} C_1 e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B7)$$

Integrating gives the interface shape about the equilibrium interface:

$$\eta = (2m+1) \frac{\pi}{L} \frac{C_1}{n} e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B8)$$

The displacement from equilibrium is assumed to be zero at the ends of the wire,  $x = 0$  and  $x = L$ . This condition is satisfied by the chosen sine function. If  $n$  is positive, the displacement will grow with time, and the interface will be unstable.

The potential functions (eqs. (B6)) are now substituted into equations (B5) to give

$$p_l = p_{l,o} - g\rho_l y + \rho_l C_1 n e^{-(2m+1)(\pi/L)y} e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B9a)$$

$$p_v = p_{v,o} - g\rho_v y - \rho_v C_1 n e^{(2m+1)(\pi/L)y} e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B9b)$$

The pressure difference across the interface is then given by

$$(p_v - p_l)_{y=\eta \approx 0} = (p_{v,o} - p_{l,o}) + g\eta(\rho_l - \rho_v) - (\rho_l + \rho_v) C_1 n e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B10)$$

where the quantity  $e^{(2m+1)(\pi y/L)}$  has been set equal to unity as an approximation for very small values of  $y$ .

The pressure difference across the interface must also agree with that computed from the surface-tension forces. The pressure difference is computed from the principal radii of curvature as

$$p_v - p_l = \sigma \left( \frac{1}{R_x} + \frac{1}{R_c} \right) \quad (B11)$$

For small displacements  $1/R_x \approx -\partial^2 \eta / \partial x^2$ . The radius of curvature  $R_c$ , in the circumferential direction is obtained from the cross-sectional shape of the film. That the details of this shape have not been well established was recently pointed out in the discussion section at the end of reference 18. Figures 7(b) and (c) (p. 21) show photographs at a higher magnification than those

in figure 5 (pp. 17 and 18) for the vapor film on a horizontal wire in Earth gravity and in reduced gravity ( $0.014 g_n$ ). At the locations where the vapor film is relatively undisturbed and has a minimum thickness, the film appears to be quite symmetric about the wire even in Earth gravity. Although for higher gravity fields the film definitely becomes thinner along the bottom of the wire, as discussed in reference 12, this is evidently not the case for the normal or reduced-gravity conditions observed herein. Hence, for the present analysis, a symmetric circular film cross section will be assumed, as shown in figure 7(d) (p. 21). In this instance, when there is a deflection of the film of magnitude  $\eta$ , the circumferential radius of curvature  $R_c$  becomes

$$R_c = R + \Delta R + \eta$$

Substituting  $R_x$  and  $R_c$  into equation (B11) and equating the result to equation (B10) give

$$-\sigma \frac{\partial^2 \eta}{\partial x^2} + \frac{\sigma}{R + \Delta R + \eta} = (p_{v,o} - p_{l,o}) + g\eta(\rho_l - \rho_v) - (\rho_l + \rho_v)C_1 n e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B12)$$

For an equilibrium interface when  $\eta = 0$ , equation (B12) with the use of equation (B8) reduces to

$$p_{v,o} - p_{l,o} = \frac{\sigma}{R + \Delta R} \quad (B13)$$

so that equation (B12) becomes, after subtracting equation (B13),

$$-\sigma \frac{\partial^2 \eta}{\partial x^2} + \sigma \left( \frac{1}{R + \Delta R + \eta} - \frac{1}{R + \Delta R} \right) = g\eta(\rho_l - \rho_v) - (\rho_l + \rho_v)C_1 n e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B14)$$

Assuming  $\eta \ll R$ ,  $\eta \ll \Delta R$ , and  $\Delta R$  not necessarily small compared with  $R$  gives

$$-\sigma \left[ \frac{\partial^2 \eta}{\partial x^2} + \frac{\eta}{(R + \Delta R)^2} \right] = g\eta(\rho_l - \rho_v) - (\rho_l + \rho_v)C_1 n e^{n\tau} \sin(2m+1) \frac{\pi x}{L} \quad (B15)$$

The displacement  $\eta$  is substituted from equation (B8), and equation (B15) can then be rearranged to give

$$n^2 = \frac{\sigma}{\rho_l + \rho_v} \left[ \frac{(2m+1) \frac{\pi}{L}}{(R + \Delta R)^2} - (2m+1)^3 \left( \frac{\pi}{L} \right)^3 \right] + \frac{\rho_l - \rho_v}{\rho_l + \rho_v} (2m+1) \frac{\pi}{L} g \quad (B16)$$

For the displacement to grow with time,  $n$  has to be a real number greater than zero, as seen from equation (B8). Hence, for unstable conditions, the right side of equation (B16) must be positive. The fact that  $n$  could then be a negative number (because there is a square root involved) is neglected as it is known physically that the disturbances do amplify. (Both positive and negative solutions exist, but the negative one decays with time.) Hence, for an unstable interface

$$\sigma \left[ \frac{1}{(R + \Delta R)^2} - (2m + 1)^2 \left( \frac{\pi}{L} \right)^2 \right] + g(\rho_l - \rho_v) > 0$$

and

$$m < -\frac{1}{2} + \frac{L}{2\pi} \left[ \frac{g}{\sigma} (\rho_l - \rho_v) + \frac{1}{(R + \Delta R)^2} \right]^{1/2} \quad (B17)$$

The corresponding unstable wavelength is

$$\lambda = \frac{2L}{2m + 1} > 2\pi \left[ \frac{g}{\sigma} (\rho_l - \rho_v) + \frac{1}{(R + \Delta R)^2} \right]^{-1/2} \quad (B18)$$

This equation is of the same general form as that obtained in reference 18. To obtain the value of  $m$  for which the waves will be most unstable, the value of  $n$  is maximized with respect to  $m$  by letting  $\partial n / \partial m = 0$ , which gives by using equation (B16)

$$m_d = -\frac{1}{2} + \frac{L}{2\sqrt{3}\pi} \left[ \frac{g}{\sigma} (\rho_l - \rho_v) + \frac{1}{(R + \Delta R)^2} \right]^{1/2} \quad (B19)$$

$$\lambda_d = 2\sqrt{3}\pi \left[ \frac{g}{\sigma} (\rho_l - \rho_v) + \frac{1}{(R + \Delta R)^2} \right]^{-1/2} \quad (B20)$$

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